PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Imaging the surface of Altair and a MIRC update

John D. Monnier, M. Zhao, E. Pedretti, N. Thureau, M. Ireland, et al.

John D. Monnier, M. Zhao, E. Pedretti, N. Thureau, M. Ireland, P. Muirhead, J.-P. Berger, R. Millan-Gabet, G. Van Belle, T. ten Brummelaar, H. McAlister, S. Ridgway, N. Turner, L. Sturmann, J. Sturmann, D. Berger, A. Tannirkulam, J. Blum, "Imaging the surface of Altair and a MIRC update," Proc. SPIE 7013, Optical and Infrared Interferometry, 701302 (15 July 2008); doi: 10.1117/12.789754

Event: SPIE Astronomical Telescopes + Instrumentation, 2008, Marseille, France

Imaging the Surface of Altair and a MIRC Update

John D. Monnier[a], M. Zhao[a], E. Pedretti[b], N. Thureau[b], M. Ireland[c], P. Muirhead[d], J.-P. Berger[e], R. Millan-Gabet[f], G. Van Belle[g], T. ten Brummelaar[h], H. McAlister[h], S. Ridgway[i], N. Turner[h], L. Sturmann[h], J. Sturmann[h], D. Berger[a], A. Tannirkulam[a], J. Blum[a]

[a]Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109;
[b]University of St. Andrews, Scotland, UK;
[c]University of Sydney, Sydney, Australia;
[d]Cornell University, Ithaca, NY;
[e]Laboratoire d'Astrophysique de Grenoble, France;
[f]Michelson Science Center, Pasadena, CA;
[g]European Southern Observatory, Garching, Germany;
[h]CHARA, Georgia State University, Atlanta, GA;
[i]National Optical Astronomy Observatory, Tucson, AZ

ABSTRACT

We report the first scientific results from the Michigan Infrared Combiner (MIRC), including the first resolved image of a main-sequence star besides the Sun. Using the CHARA Array, MIRC was able to clearly resolve the well-known elongation of Altair's photosphere due to centrifugal distortion, and was also able to unambiguously image the effect of gravity darkening. In this report, we also show preliminary images of the interacting binary β Lyr and give an update of MIRC performance.

Keywords: interferometry, infrared, rapid rotation, fiber optics, altair, beta lyrae

1. INTRODUCTION

The University of Michigan optical interferometry group – led by Professor John Monnier – has built the Michigan Infrared Combiner as an "imaging combiner" for the Georgia State University CHARA[1,2] Array (PI: Hal McAlister). MIRC was commissioned in Fall 2005 and the first scientific paper was published in 2007.[3] In this article, we report on recent upgrades to the MIRC combiner, highlight exciting discoveries, and discuss the future of this project.

2. MICHIGAN INFRARED COMBINER

2.1 Summary

The MIRC combiner was first described at the 2004 SPIE meeting by Monnier et al.[4] and a description of commissioning results can be found in the 2006 SPIE proceedings.[5]

MIRC is an image-plane combiner, allowing simultaneous measurements of all available baselines and closure phases in the full 6-telescope CHARA array. The beams from all telescopes are arranged in a linear non-redundant pattern and then imaged onto the slit of an infrared spectrograph at the backend (see Figure 1). In order to allow precision calibration of visibility amplitudes and closure phases, the synthetic pupil is formed using light transported and spatially-filtered by single-mode fibers for optical stability.[6] A non-deviating prism pair (R$\sim$35) or low-resolution grism (R$\sim$150,450) on the output mitigates dispersion problems and bandwidth-smearing of data (especially important with the long CHARA baselines).

Here I only briefly summarize the main properties of the MIRC combiner:

Further author information: (Send correspondence to J.D.M.)
J.D.M.: E-mail: monnier@umich.edu, Telephone: 1 734 763 5822

Optical and Infrared Interferometry, edited by Markus Schöller, William C. Danchi, Françoise Delplancke
Proc. of SPIE Vol. 7013, 701302, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.789754

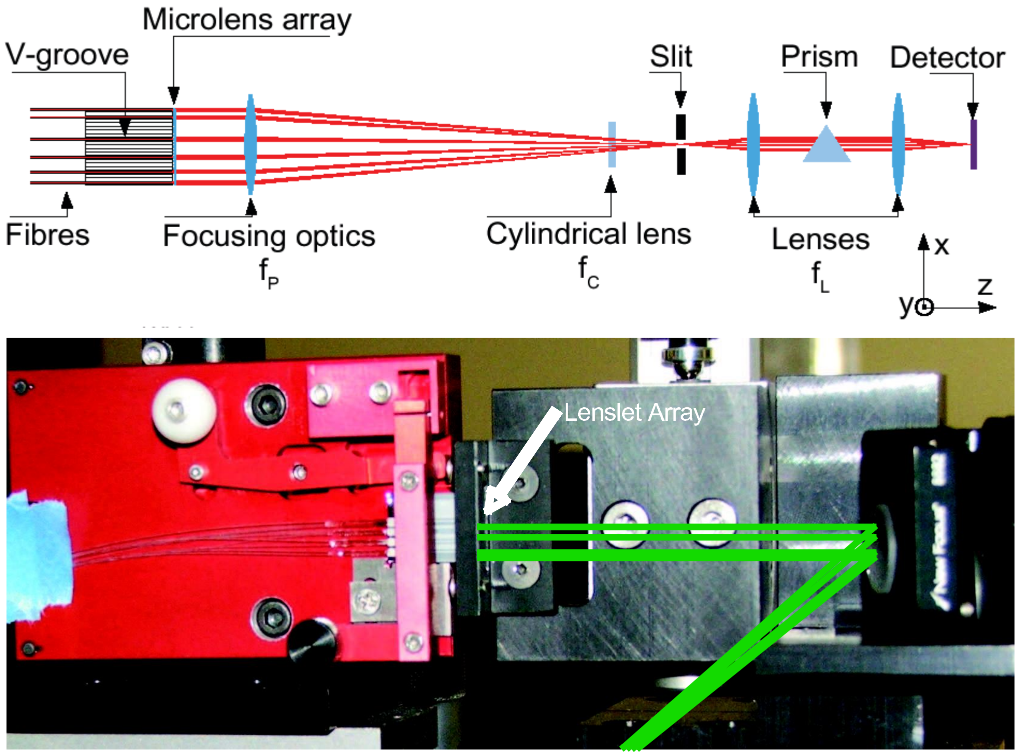

Figure 1. The overall schematic of the MIRC instrument can be seen in the top diagram above. Once light from each telescope is focused into a single mode fiber, the fibers are arranged into a non-redundant pattern. The bottom image shows the fibers packaged in a silicon v-groove array, the location of the collimator lenslet array, and a spherical silver mirror that focuses the beams to produce interference fringes at the input slit of the camera-spectrometer. The proposed "photometric channels" (discussed in Section 2.2) will pick-off the beams just after the lenslet array and before the spherical mirror pictured here.

- Image Plane Combination: 6 telescopes, 15 visibilities, 20 closure phases simultaneously (and measurements of closure *amplitudes* for the first time); to date, we have used only 4 telescopes
- 1.45-2.5 microns (H and K bands)
- Low-resolution spectroscopy, R$\sim$35, 150 or 450
- Spatial filtering using single-mode fibers
- Integration with a separate fringe tracker (CHAMP, see Berger et al.[7]).

2.2 Performance and Recent Upgrades

2.2.1 Photometric Estimators

The original MIRC system had no way to estimate the telescope flux in each fiber except through shutter sequences done before and after fringe acquisition (similar to the technique at Keck and Palomar Testbed Interferometers). We found this procedure to be wholly inadequate – for a 4-beam combiner, errors in the flux ratio enter into the visibility calibration linearly. This is in contrast to a two-beam combiner where the beam ratio only weakly affect the system visibility when one can estimate the total two-beam flux from the detector combined light. For a 4-beam combiner, we only have access (instantaneously) to the sum of all 4 beams and thus it is critical to know individual beam contributions for even crude calibration. Visibility-Squared calibration

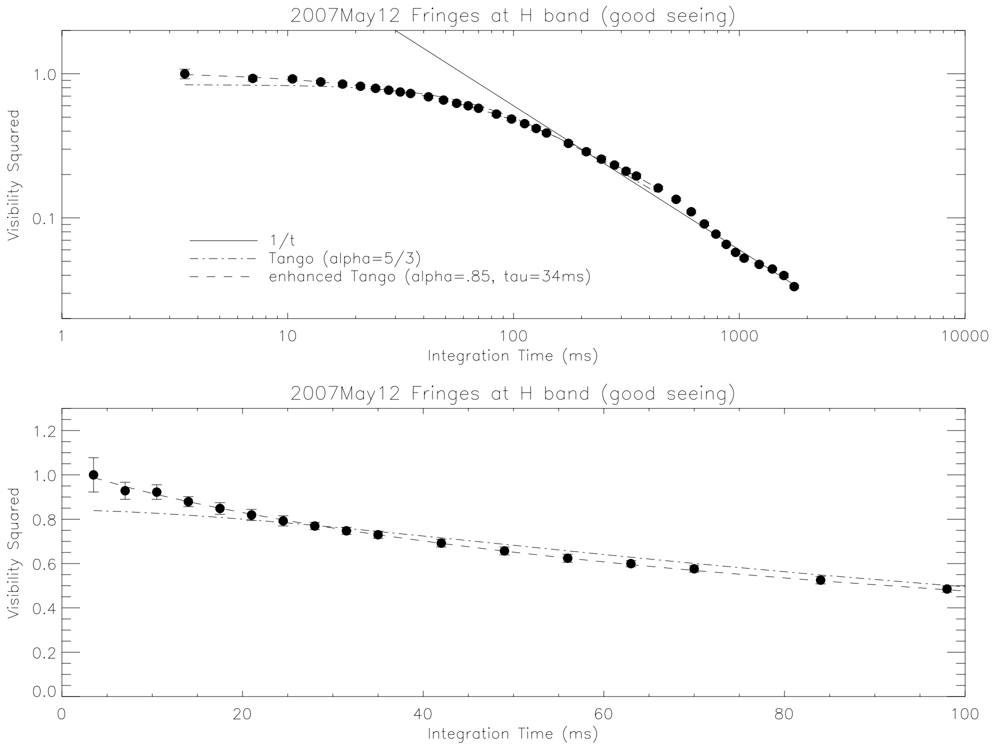

Figure 2. This figure shows how the observed fringe visibility-squared (for one MIRC baseline) varies as the coherent integration time is increased (in software). The behavior fits a modified Davis & Tango[8] function.

errors could be very large (50%) since the fiber couplng for a given telescope can change dramaticly in a short time frame – due to drifts, telescope drive oscillations, or seeing changes.

First, we were able to markedly improve this situation through a software change. The light pattern that emerges from each fiber is somewhat unique due to internal interference effects through the spectrograph ("fringing") and image quality differences (ideally, each pattern should be a nearly-perfect Gaussian, but this is not the case in practice for MIRC). Thus – we were able to estimate the contributions from each fiber in a combined data frame (fringe data) by finding the linear combination of individual (known) beam profiles that best match the observed combined profile. Tests show that this generally works well – with errors of ∼10-20% in visibility-squared for good signal-to-noise and when beam fluxes are well matched (typically this is done as an average over a 3.5 second integration). Some degradation is seen if one beam is substantially brighter than the others, due presumably to non-linearities in detector performance that are not balanced between the beams and not properly modelled yet in software.

In order to improve upon this situation, we installed choppers before the fiber injection modules in Summer 2006. After some experimentation, we adopted the following setup. The 4 telescope beams are interrupted at frequencies of 55, 65, 75, and 85 Hz respectively using chopper blades consisting of vanes 8mm thick that spin through the 20mm CHARA (reduced) beams. This has the effect of changing the transmission and the image of the star as it is projected onto the single-mode fiber. The combination of the blocked light and the variable coupling induced by the image changes causes a nearly 100% modulation of the signal. We use chopper hardware from Stanford Research Systems (SR540); however, this system is not ideal since the chopper spin rate is not done through a control loop and we observe that the spin frequency show some variation (many %) over a few seconds thus reducing our signal-to-noise ratio.

The chopper system has made our calibration more reliable, achieving 10-20% calibration for a fainter objects than can be done with the "fiber profile" method and with better performance in the case of large beam flux

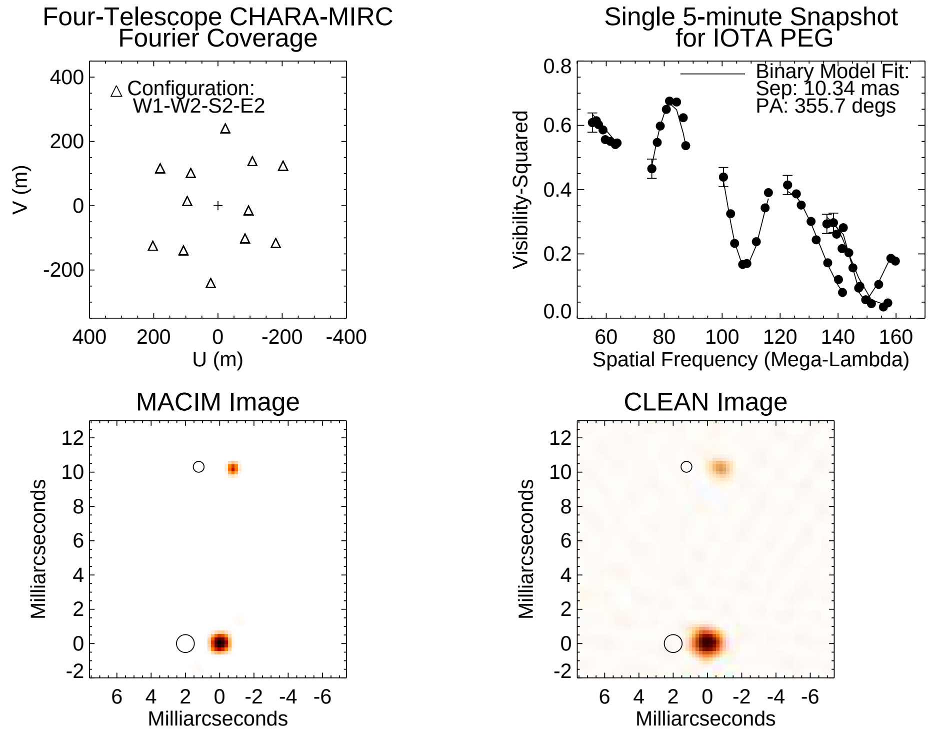

Figure 3. This figure summarizes the validation tests of the MIRC imaging pipeline. The top-left panel shows the snapshot Fourier coverage using 4 telescopes of the CHARA Array. The top-right panel shows the visibility results for the corresponding 6 baselines – note the 4 closure triangles are not shown here. The bottom panels show the aperture synthesis imaging using the MACIM code as well as the CLEAN algorithm. The circles show the binary model of Iota Peg based on fitting directly to the interferometric observables – there is good agreement between the images and the model results. These results were first presented in Monnier et al.[3]

ratios. The main downsides for this approach are that our limiting magnitude is set by the ability to calibrate V^2 and also that the choppers are not stable enough. Another critical problem with this method is that the choppers are located before the fiber, which means that the modulation efficiency actual depends on the alignment of the starlight onto the fiber core. The modulation efficiency has to be measured at a different time (using shutters) than the fringes, thus we are vulnerable to miscalibrations when the system is not stable or when changes in seeing occur, etc.

In 2007, we took one further step to improve the chopper calibration. The SR540 choppers are equipped with photo-interrupters that produce TTL outputs. While these signals (unfortunately) are not used for real-time phase-lock loop control to optimize frequency stability, we can digitize these signals and do a post-detection, software synchronization. We use a webDAQ/100 to digitize the signals from the 4 choppers along with a synchronization pulse at the start of each data block (using PC parallel port). The MIRC pipeline was modified to use this additional data stream (when available) and this has improved the signal-to-noise of the measurement by stabilizing the chopper frequencies (in software), but has not reduced the fundamental limitations of the chopper method.

Since we are using single-mode fibers, we strive to attain $\sim$1% calibration as has been shown for the FLUOR[9] and VINCI[10] instruments. We are proceeding to install a beamsplitter which will be positioned just after the microlens array. This will split the light after spatial filtering and thus will be a reliable estimate of the fiber coupling, eliminating the image-quality and alignment dependencies we currently suffer from. Following this split, the tiny photometric beams will be re-collimated into multi-mode fibers and these fibers will be arranged into a row of output fibers spaced equally 250μm apart. This row of fibers will be positioned at the input the

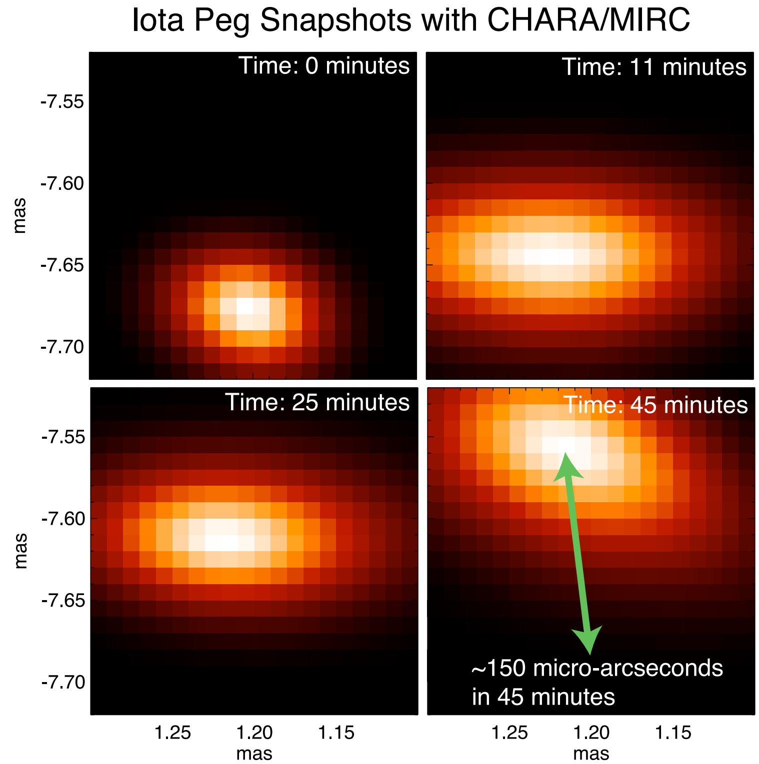

Figure 4. This figure highlights the incredible angular resolution of the CHARA Array for binary studies. The four panels show the best-fit separation between the two components of iota Peg as a function of time – four epochs spread over 45 minutes. The shaded regions represent the likelihood function based on a χ^2 analysis. We can see that each individual 5-minute data snapshot localizes the binary separation to within about 20 *MICRO*-arcseconds and the orbital motion towards the north is definitively detected in this short time series. Such precision could be used for detecting the orbital wobble from an unseen planetary companion, similar to the Palomar Testbed Interferometer astrometry survey by Muterspaugh et al.[11]

spectrograph, such that the image will be aligned with a quadrant neighboring the main quadrant containing the fringe patterns. Since all 4 quadrants of the PICNIC detector are currently being readout in parallel, the photometric data will be taken simultaneous with the fringe data and should allow high precision calibration of the visibilities. The main difficulty in this upgrade is a practical one not an expensive one – designing and building the custom mounts and installing the necessary optics in the very confined and limited space on the CHARA-MIRC table.

2.2.2 Spectral Tilts

We discovered that as the star image drifts relative to the core of the single-mode fiber, the injection efficiency develops a large spectral tilt. In practice, this means that the flux ratio between the edges of H band can vary by up to a factor of 2 or 3. We believe the cause of this tilt it straightforward – the mode field diameter of the single mode is physically larger for longer wavelengths, thus more light is coupled at longer wavelengths when the star light is mistakenly focused off-center from the fiber core (note that all CHARA optics before fiber are mirrors except one dichroic and 2 vacuum windows). Clearly, this variation must be taken into account to accurately calibrate each of the individual spectral channels and the latest MIRC data analysis pipeline attempts to do this. An internal study shows the spectral tilt is accurately characterized as a linear tilt which eases data analysis.

2.2.3 Closure Amplitudes

We have investigated the use of closure amplitudes[12] since MIRC measures fringes from 4 telescopes simultaneously. In some cases, the closure amplitudes do offer a more robust observable than the individual visibilities, but generally only when there are big miscalibrations from changing fiber injection efficiencies (i.e., due to unusual drifts or poor initial fiber alignments). In most cases, closure amplitudes have not proven to be significantly better calibrated than the individual visibilities. Speculatively, this could be due to changes in the coherence time and we have begun exploring this possibility (see next subsection).

2.2.4 Coherent integration

With UM graduate student Jen Blum, we began measuring the coherence properties of the MIRC data. For MIRC, we take continuous fringe data blocks for 5.3 seconds with frametimes of 3.5 milliseconds. This allows us to measure the coherence properties from short to long effective integration times. Figure 2 shows results (shown both linearly and logarithmically) of how the measured fringe visibility varies as we increase the integration time (normalized to unity at t=0 s). The functional form of the coherence function found by Davis and Tango[8] can be used if one generalizes their equation for non-Kolmogorov α parameter. In this figure, we plot the best fit Davis & Tango function along with the best-fit function using free α. The differences in functional form probably are not due to a different turbulent structure function, but could be due to simplifying assumptions (such as telescope aperture $<<$ r_0, free-space combiner instead of fibers) that do not hold for CHARA-MIRC.

While we have yet to integrate this analysis into our data pipeline (due to the large increase in computation required in current implementation), we expect this line of research will improve our calibration, allow optimum coherent integrations for faint targets, and will be invaluable for calibrating data taken using the new CHARA fringetracker (see §4).

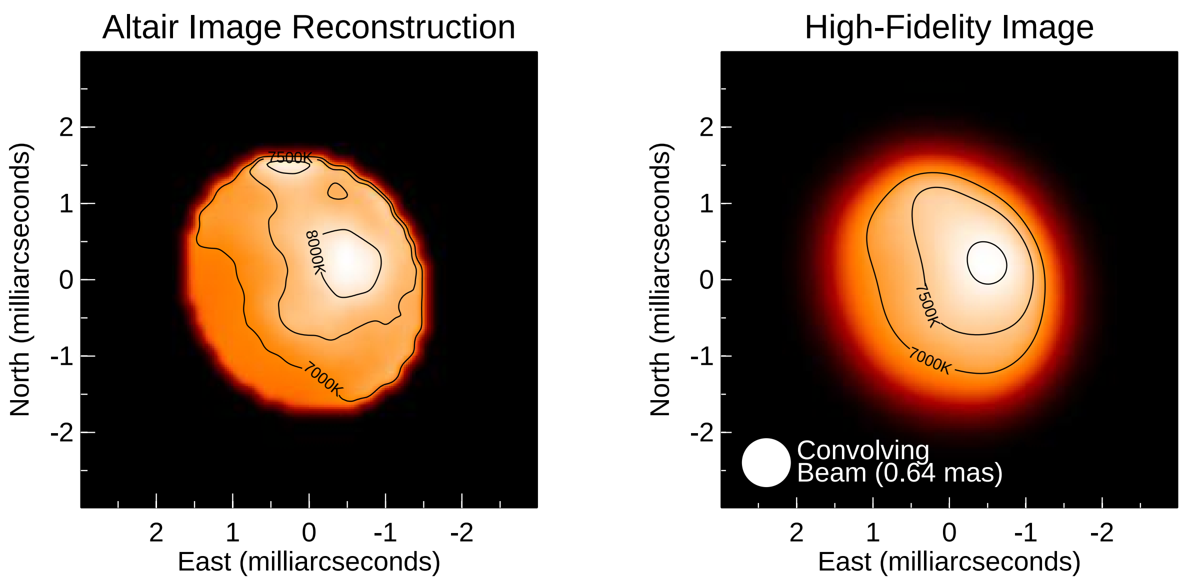

Figure 5. This figure (reproduced from Monnier et al.[3]) shows the first resolved image of a main-sequence star beside the Sun. The left panel shows the image reconstruction using the MACIM[13] software combined with the constraint that all the image flux arises inside an elliptical boundary. The right panel shows the same image convolved with a 0.6 mas restoring beam, degrading the angular resolution but increasing the image fidelity.

3. SCIENCE HIGHLIGHTS

3.1 Iota Peg: a test binary

Iota Peg is a nearby binary with a period of 10.2 days and a semi-major axis of 10.33 mas, according to the recent orbit determination of Boden et al.[14] The high brightness and close separation makes Iota Peg an ideal calibration source for CHARA-MIRC and new interferometers with >100m baselines. Iota Peg was observed on multiple occasions in 2006 by CHARA-MIRC for testing purposes.

Figure 3 shows a summary of our data and first test of imaging. We analyzed the visibility and closure phases using 3 methods: model-fitting, the MACIM[13] software for imaging and the CLEAN[15] method (with self-calibration). You can see in this figure that the three methods give comparable results.

Next, we studied the precision and reliability of our binary model fits. Figure 4 shows the likelihood surfaces for the binary separation vector for iota Peg, localizing the component separation with a precision of $\sim$20 *MICRO*-arcseconds using less than 5 minutes of data. To prove this, we also show how we track the orbital motion of the binary over a 45 minute period, clearly detecting a proper motion of about 0.15 milli-arcseconds.

3.2 Altair: a rapid rotator

In 2007, we published the first science result from MIRC: an image of the star Altair.[3] Van Belle et al.[16] first used the Palomar Testbed Interferometer (PTI) to resolve Altair to be elongated – confirming the spectroscopic result that it is rapidly rotating at $\sim$90% of breakup. Using 4 telescopes and the 6 corresponding baselines of CHARA, we achieved more then $3\times$ better angular resolution than the PTI results and have been able to make a true image. Figure 5 shows our results, reprinted from the *Science* Letter. We can see the elongation of the star associated the centrifugal distortion and see the effect of "gravity darkening," the equator being significantly cooler than the pole ($\Delta T \sim 1800$ K !!). Please see our paper[3] for more information on Altair and other scientific details. In addition to Altair, we are also preparing a manuscript[17] with detailed models and images of α Oph, α Cep, and Vega.

In Zhao et al.,[17] we present a new method for measuring the mass of a single rapidly-rotating star through the combination of imaging and spectroscopic data. The elongation measured and modelled with the interferometer gives the fraction of breakup speed, which is a dimensionless ratio between the centrifugal force and gravitational force at the equator surface. By isolating the equatorial speed using spectroscopy and correcting for the inclination effect through a model, we can then estimate the gravitational force. Since this method does depend on some assumptions (such as solid-body rotation), we plan to test this method using a star in a known binary system.

3.3 Beta Lyr: an interacting binary

With the longest baselines in the world, CHARA can use the unprecedented high angular resolution to image new classes of objects, including interacting binaries such as Spica, Algol, and β Lyrae for the first time. Zhao et al.[18] presented the first resolved images of the interacting and eclipsing β Lyr, showing first signs of the elongated, Roche-lobe filling primary and clearly resolving the gas disk around the mass gainer. In Figure 6 we show images taken over half the binary period along with the first astrometric orbit, derived from our CHARA-MIRC data.

3.4 Exopolanets

Our group is keenly interested to use the high closure phase stability of MIRC for detecting exoplanets. Models[19,20] predict that hot Jupiters could have closure phases as high as 0.15 degrees in the H band at CHARA (best candidates: Ups And, Tau Boo, 51 Peg). Currently, we are limited by photon noise and calibration precision and we present a recent study of data on Ups And in Figure 7. Not all epochs of data show this high level of stability and we are currently researching the cause(s) of the systematic errors. It is exciting that our formal errors are nearly at the level expected to detect the hot Jupiter directly.

Ming Zhao presents a more thorough (preliminary) analysis elsewhere in this volume[21] and also some work was presented in the conference proceeding[20] for IAU 249. Here I summarize the remaining improvements that we feel are needed to reach the goal of direct detection of hot Jupiters with MIRC:

- Image quality improvements for the 1-m CHARA telescopes are needed to increase coupling of light into the fiber.
- Use of fringe tracker to optimize data collection.
- Eliminate systematic errors through better estimates of the telescope beam fluxes – see §2.2 for our planned approach.

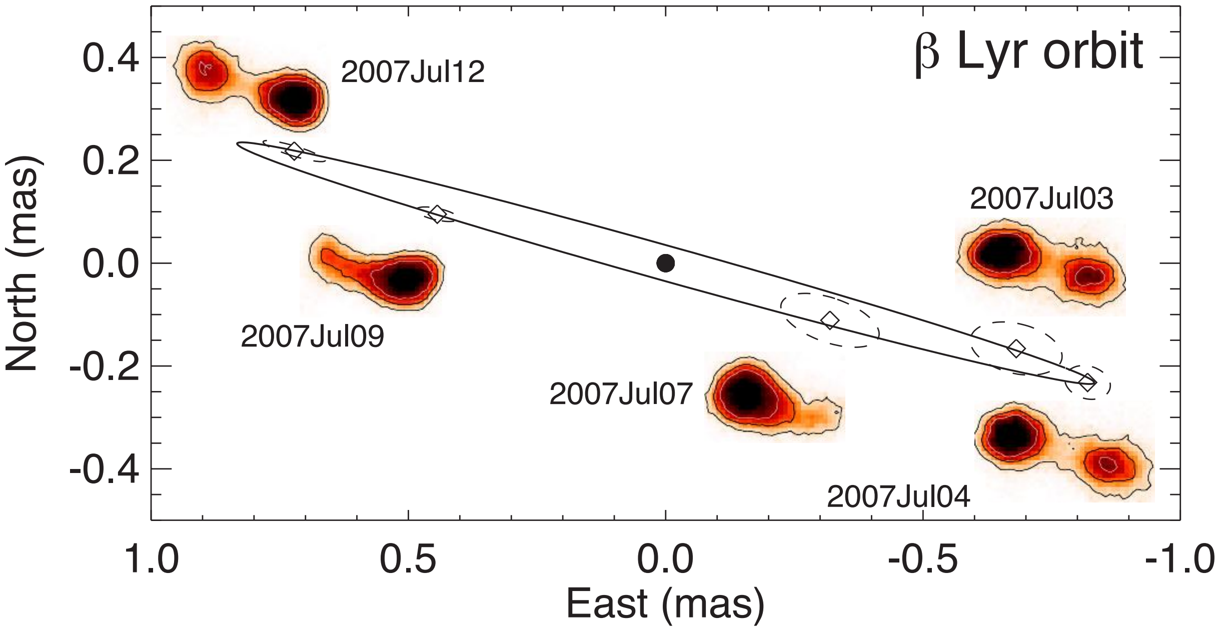

Figure 6. This figure shows CHARA-MIRC imaging results for the interacting binary system β Lyrae from Zhao et al.[18] The orbit is shown along with the MACIM image reconstructions for 5 epochs. The high resolution of CHARA ($\sim$0.5 milliarcseconds) allows the components to be cleanly resolved for the first time and for the first ever astrometric orbit determination.

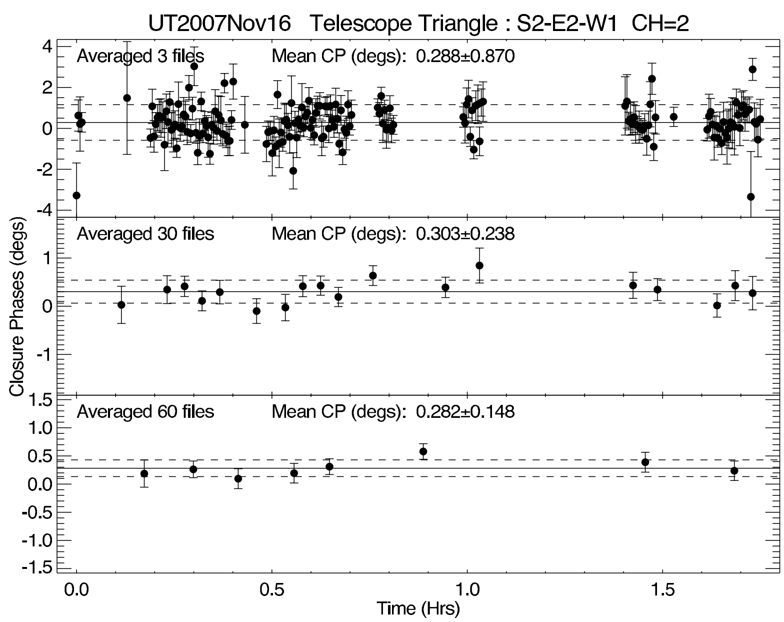

Figure 7. This figure shows recent precision closure phase results for Ups And. The variation observed is a few times larger than that expected for some model atmospheres of Ups And and we believe the observed variations are likely due to noise and/or some uncorrected systematic errors. This is an active area of research for our team, especially for Ming Zhao who is devoting signficant Ph.D. dissertation research towards direct detection of exoplanets with MIRC.

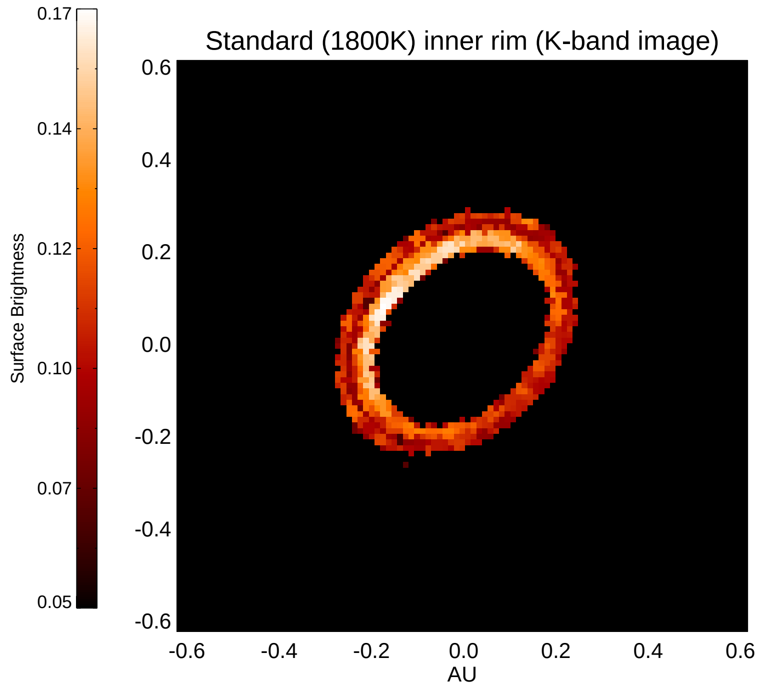

Figure 8. This figure shows the expected K-band image for the inner hot disk for MWC 275, following the study of Tannirkulam et al.[24] After commissioning of the fringe tracker CHAMP, we expect to observe this object and many others YSOs to allow first ever imaging of the inner AU.

- Lastly, it might be necessary to re-design the achromatic doublet in the MIRC spectrograph to remove internal "fringing" that happens within each beam.

Lastly, we point out that MIRC might be able to detect the shadow of a transiting planet directly with some sensitivity improvements. This possibility was recently studied by Van Belle et al.[22]

4. FUTURE WORK

While we discussed future hardware upgrades to MIRC in §2.2, here we remark on how MIRC science will be improved through integration with the new CHARA fringetracker called CHAMP.[7]

Our group at Michigan has built and will commission the CHARA-Michigan Phasetracker (CHAMP) in 2008. This instrument was first described in the last SPIE proceedings[23] and we have an updated final description of the instrument elsewhere in these proceedings.[7]

The primary science driver for CHAMP is to allow imaging of young stellar objects with the MIRC combiner. Currently, YSOs are too faint to observe with MIRC but the fringe tracker should increase our fringe tracking limit by 2-3 magnitudes, allowing these objects to be observed. Tannirkulam et al.[24] recently presented first YSO results using the 2-telescope combiner CLASSIC at CHARA, and his modeling results show the potential for imaging disks using MIRC (see Figure 8). Please see the Tannirkulam et al.[25] paper elsewhere in these proceedings for more information on observing Young Stellar Objects with CHARA.

ACKNOWLEDGMENTS

This work has been supported by the University of Michigan, the National Science Foundation and NASA.

REFERENCES

[1] McAlister, H. A., ten Brummelaar, T. A., Gies, D. R., Huang, W., Bagnuolo, Jr., W. G., Shure, M. A., Sturmann, J., Sturmann, L., Turner, N. H., Taylor, S. F., Berger, D. H., Baines, E. K., Grundstrom, E., Ogden, C., Ridgway, S. T., and van Belle, G., "First Results from the CHARA Array. I. An Interferometric and Spectroscopic Study of the Fast Rotator α Leonis (Regulus)," ApJ **628**, 439–452 (July 2005).

[2] ten Brummelaar, T. A., McAlister, H. A., Ridgway, S. T., Bagnuolo, Jr., W. G., Turner, N. H., Sturmann, L., Sturmann, J., Berger, D. H., Ogden, C. E., Cadman, R., Hartkopf, W. I., Hopper, C. H., and Shure, M. A., "First Results from the CHARA Array. II. A Description of the Instrument," ApJ **628**, 453–465 (July 2005).

[3] Monnier, J. D., Zhao, M., Pedretti, E., Thureau, N., Ireland, M., Muirhead, P., Berger, J.-P., Millan-Gabet, R., Van Belle, G., ten Brummelaar, T., McAlister, H., Ridgway, S., Turner, N., Sturmann, L., Sturmann, J., and Berger, D., "Imaging the Surface of Altair," *Science* **317**, 342– (July 2007).

[4] Monnier, J. D., Berger, J.-P., Millan-Gabet, R., and Ten Brummelaar, T. A., "The Michigan Infrared Combiner (MIRC): IR imaging with the CHARA Array," in [*New Frontiers in Stellar Interferometry, Proceedings of SPIE Volume 5491. Edited by Wesley A. Traub. Bellingham, WA: The International Society for Optical Engineering, 2004., p.1370*], Traub, W. A., ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **5491**, 1370–+ (Oct. 2004).

[5] Monnier, J. D., Pedretti, E., Thureau, N., Berger, J.-P., Millan-Gabet, R., ten Brummelaar, T., McAlister, H., Sturmann, J., Sturmann, L., Muirhead, P., Tannirkulam, A., Webster, S., and Zhao, M., "Michigan Infrared Combiner (MIRC): commissioning results at the CHARA Array," in [*Advances in Stellar Interferometry. Edited by Monnier, John D.; Schöller, Markus; Danchi, William C.. Proceedings of the SPIE, Volume 6268, pp. 62681P (2006).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6268** (July 2006).

[6] Coudé du Foresto, V., Ridgway, S., and Mariotti, J.-M., "Deriving object visibilities from interferograms obtained with a fiber stellar interferometer," A&AS **121**, 379–392 (Feb. 1997).

[7] Berger, D. H., Monnier, J. D., Millan-Gabet, R., ten Brummelaar, T. A., Muirhead, P., Pedretti, E., and Thureau, N., "CHARA Michigan phase-tracker (CHAMP)," in [*Optical and Infrared Interferometry. Edited by Schöller, Markus; Proceedings of the SPIE, in press (2008).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* (2008).

[8] Davis, J. and Tango, W., "Measurement of the Atmospheric Coherence Time," PASP **108**, 456–+ (May 1996).

[9] Perrin, G., "The calibration of interferometric visibilities obtained with single-mode optical interferometers. Computation of error bars and correlations," A&A **400**, 1173–1181 (Mar. 2003).

[10] Kervella, P., Ségransan, D., and Coudé du Foresto, V., "Data reduction methods for single-mode optical interferometry. Application to the VLTI two-telescopes beam combiner VINCI," A&A **425**, 1161–1174 (Oct. 2004).

[11] Muterspaugh, M. W., Lane, B. F., Kulkarni, S. R., Burke, B. F., Colavita, M. M., and Shao, M., "Limits to Tertiary Astrometric Companions in Binary Systems," ApJ **653**, 1469–1479 (Dec. 2006).

[12] Monnier, J. D., "Phases in interferometry," *New Astronomy Review* **51**, 604–616 (Oct. 2007).

[13] Ireland, M. J., Monnier, J. D., and Thureau, N., "Monte-Carlo imaging for optical interferometry," in [*Advances in Stellar Interferometry. Edited by Monnier, John D.; Schöller, Markus; Danchi, William C.. Proceedings of the SPIE, Volume 6268, pp. 62681T (2006).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6268** (July 2006).

[14] Boden, A. F., Koresko, C. D., van Belle, G. T., Colavita, M. M., Dumont, P. J., Gubler, J., Kulkarni, S. R., Lane, B. F., Mobley, D., Shao, M., Wallace, J. K., The PTI Collaboration, and Henry, G. W., "The Visual Orbit of IOTA Pegasi," ApJ **515**, 356–364 (Apr. 1999).

[15] Högbom, J. A., "Aperture Synthesis with a Non-Regular Distribution of Interferometer Baselines," A&AS **15**, 417–+ (June 1974).

[16] van Belle, G. T., Ciardi, D. R., Thompson, R. R., Akeson, R. L., and Lada, E. A., "Altair's Oblateness and Rotation Velocity from Long-Baseline Interferometry," ApJ **559**, 1155–1164 (Oct. 2001).

[17] Zhao, M., Monnier, J. D., Millan-Gabet, R., Pedretti, E., ten Brummelaar, T. A., McAlister, H., Turner, N., Sturmann, J., and Sturmann, L., "Imaging the rapid rotators α Oph and α Cep," ApJ(in prep) (2008).

[18] Zhao, M., Gies, D., Monnier, J. D., Millan-Gabet, R., Pedretti, E., ten Brummelaar, T. A., McAlister, H., Turner, N., Sturmann, J., and Sturmann, L., "Imaging the interacting and eclipsing binary β Lyrae," ApJ(in press) (2008).

[19] Burrows, A., Budaj, J., and Hubeny, I., "Theoretical Spectra and Light Curves of Close-in Extrasolar Giant Planets and Comparison with Data," ApJ **678**, 1436–1457 (May 2008).

[20] Zhao, M., Monnier, J. D., ten Brummelaar, T., Pedretti, E., and Thureau, N., "Closure phase studies toward direct detection of light from hot Jupiters," in [*IAU Symposium*], *IAU Symposium* **249**, 71–77 (2008).

[21] Zhao, M., "Exoplanet studies with CHARA-MIRC," in [*Optical and Infrared Interferometry. Edited by Schöller, Markus; Proceedings of the SPIE, in press (2008).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* (2008).

[22] van Belle, G. T., "Closure Phase Signatures of Planet Transit Events," PASP **120**, 617–624 (May 2008).

[23] Berger, D. H., Monnier, J. D., Millan-Gabet, R., ten Brummelaar, T. A., Muirhead, P., Pedretti, E., and Thureau, N., "CHARA Michigan phase-tracker (CHAMP): design and fabrication," in [*Advances in Stellar Interferometry. Edited by Monnier, John D.; Schöller, Markus; Danchi, William C.. Proceedings of the SPIE, Volume 6268, pp. 62683K (2006).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6268** (July 2006).

[24] Tannirkulam, A., Monnier, J. D., Millan-Gabet, R., Harries, T. J., Pedretti, E., ten Brummelaar, T. A., McAlister, H., Turner, N., Sturmann, J., and Sturmann, L., "Strong Near-Infrared Emission Interior to the Dust Sublimation Radius of Young Stellar Objects MWC 275 and AB Aurigae," ApJ **677**, L51–L54 (Apr. 2008).

[25] Tannirkulam, A., "YSO Studies with CHARA," in [*Optical and Infrared Interferometry. Edited by Schöller, Markus; Proceedings of the SPIE, in press (2008).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* (2008).